Time-Resolved Up-Conversion of Entangled Photon Pairs

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In the process of spontaneous parametric down-conversion, photons from a pump field are converted to signal and idler photon pairs in a nonlinear crystal. The reversed process, or up-conversion of these pairs back to single photons in a second crystal, is also possible. Here, we present experimental measurements of the up-conversion rate with a controlled time delay introduced between the signal and idler photons. As a function of delay, this rate presents a full width at half maximum of 27.9 fs under our experimental conditions, and we further demonstrate that group delay dispersion of the photon pairs broadens this width. These observations are in close agreement with our calculations, thus demonstrating an ultrafast, nonclassical correlation between the signal and idler waves.

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Introduction

- Charicterizing photon wave packets

(It needs few femtoseconds temporal resolution, but optical detectors have a slow response.)

-> Two photon interference (HOM dip)

They determined the distribution of arrival time intervals between the signal and idler photons.(produced SPDC)

measured relative signal-idler group delays to a precision of 0.1fs.

-> Up conversion of Entangled Photon pairs

Overlap them spatially in a nonlinear crystal and detect the sum-frequency photon.

highly sensitive to group delay dispersion of the photon pairs(HOM interferometer is not)

Theoretical considerations.

- Two photon state of SPDC

$$\left|\Psi_{DC}\right\rangle = \left|0\right\rangle + \eta \int d^3\vec{k}_s \int d^3\vec{k}_i\, f_{DC}(\vec{k}_s, \vec{k}_i)\hat{a}_s^\dagger(\vec{k}_s)\hat{a}_i^\dagger(\vec{k}_i)\left|0\right\rangle$$

- We want to describe the up conversion of these photon pairs into single photons at the sum frequency. The up converted state is

$$\left|\Psi_{UC}\right\rangle = (1+\hat{U}_1)\left|\Psi_{DC}\right\rangle = \left(1+\frac{1}{i\hbar}\int_0^t dt' t' \hat{H}(t')\right)\left|\Psi_{DC}\right\rangle$$

Theoretical considerations.

- The up-conversion Hamiltonian can be expressed

$$\hat{H}(t) = \int d^3\vec{r} d(\vec{r}) \hat{E}_u^{(-)}(\vec{r},t) \hat{E}_s^{(+)}(\vec{r},t) \hat{E}_i^{(+)}(\vec{r},t) + H.c.$$

Electric field Operator

$$\overrightarrow{E}(\vec{r},t) = i \sum_{\vec{k}} \overrightarrow{\epsilon_{\vec{k}}} \sqrt{\frac{\hbar w}{2\epsilon_0 V}} \left(\widehat{a_{\vec{k}}} e^{-iw_k t + i\vec{k} \bullet \vec{r}} - \widehat{a_{\vec{k}}}^\dagger e^{iw_k t - i\vec{k} \bullet \vec{r}} \right)$$
$$= \overrightarrow{E^{(+)}}(\vec{r},t) + \overrightarrow{E^{(-)}}(\vec{r},t)$$

$\overrightarrow{E}^{(+)}$ Include annihilation operator $\widehat{a_{\vec{k}}}$.

$\overrightarrow{E}^{(-)}$ Include creation operator $\widehat{a_{\vec{k}}^\dagger}$..

Theoretical considerations.

- Performing the integration of up-conversion state,

$$\hat{U}_1 = \frac{2\pi}{i\hbar}\int d^3\vec{k}_u \int d^3\vec{k}_s \int d^3\vec{k}_i\, f^*_{UC}(\vec{k}_s,\vec{k}_i,\vec{k}_u)\times\delta(\omega_u-\omega_s-\omega_i)\hat{a}^\dagger_u(\vec{k}_u)\hat{a}_s(\vec{k}_s)\hat{a}_i(\vec{k}_i)$$

$$f_{UC}(\vec{k}_s,\vec{k}_i,\vec{k}_u) = \delta(k_{+x}-k_{ux})\delta(k_{+y}-k_{uy})\Phi_{UC}(\vec{k}_s,\vec{k}_i,\vec{k}_u)$$

$$\Phi_{UC}(\vec{k}_s,\vec{k}_i,\vec{k}_u) = \mathrm{sinc}(\beta)\exp(-i\beta)$$

$$k_\mu = k_{s\mu} + k_{i\mu}$$

$$\beta = \Delta k_z L/2$$

$$\Delta k_z = k_{uz} - k_{sz} - k_{iz} - k_g$$

L is the up-conversion crystal length.

$$k_g = 2\pi/\Lambda$$

Theoretical considerations.

- Assume that the SPDC pimp is monochromatic with frequency ω_p

then $$f_{DC}(\vec{k}_s, \vec{k}_i) = \delta(\omega_s + \omega_i - \omega_p) g(\vec{k}_s, \vec{k}_i)$$

$$\left|\Psi_{UC}\right\rangle = (1+\hat{U}_1)\left|\Psi_{DC}\right\rangle = \left|0\right\rangle + \kappa \int d^2\vec{k}_u^{\perp} F(\vec{k}_u^{\perp}) \times \hat{a}_u(\vec{k}_u^{\perp}, \omega_p)\left|0\right\rangle$$

this integral is over only transverse components of $\vec{k}_u$

κ includes various constants. And

$$F(\vec{k}_u^{\perp}) = \int d^2\vec{k}_s \Phi_{UC}(\omega_s, \vec{k}_s^{\perp}; \omega_p - \omega_s, \vec{k}_i^{\perp}; \omega_p, \vec{k}_u^{\perp}) \times g(\omega_s, \vec{k}_s^{\perp}; \omega_p - \omega_s, \vec{k}_i^{\perp})$$

Theoretical considerations.

- For a plane wave SPDC pump,

$$g(\omega_s, \vec{k}_s^{\perp}; \omega_p - \omega_s, \vec{k}_i^{\perp}) = \delta(k_{+x})\delta(k_{+y})\Phi_{DC}(\vec{k}_s, \vec{k}_i)$$

$$\Phi_{DC}(\vec{k}_s, \vec{k}_i) = \mathrm{sinc}(\beta)\exp(-i\beta)$$

- Assumed both crystals are characterized by same β

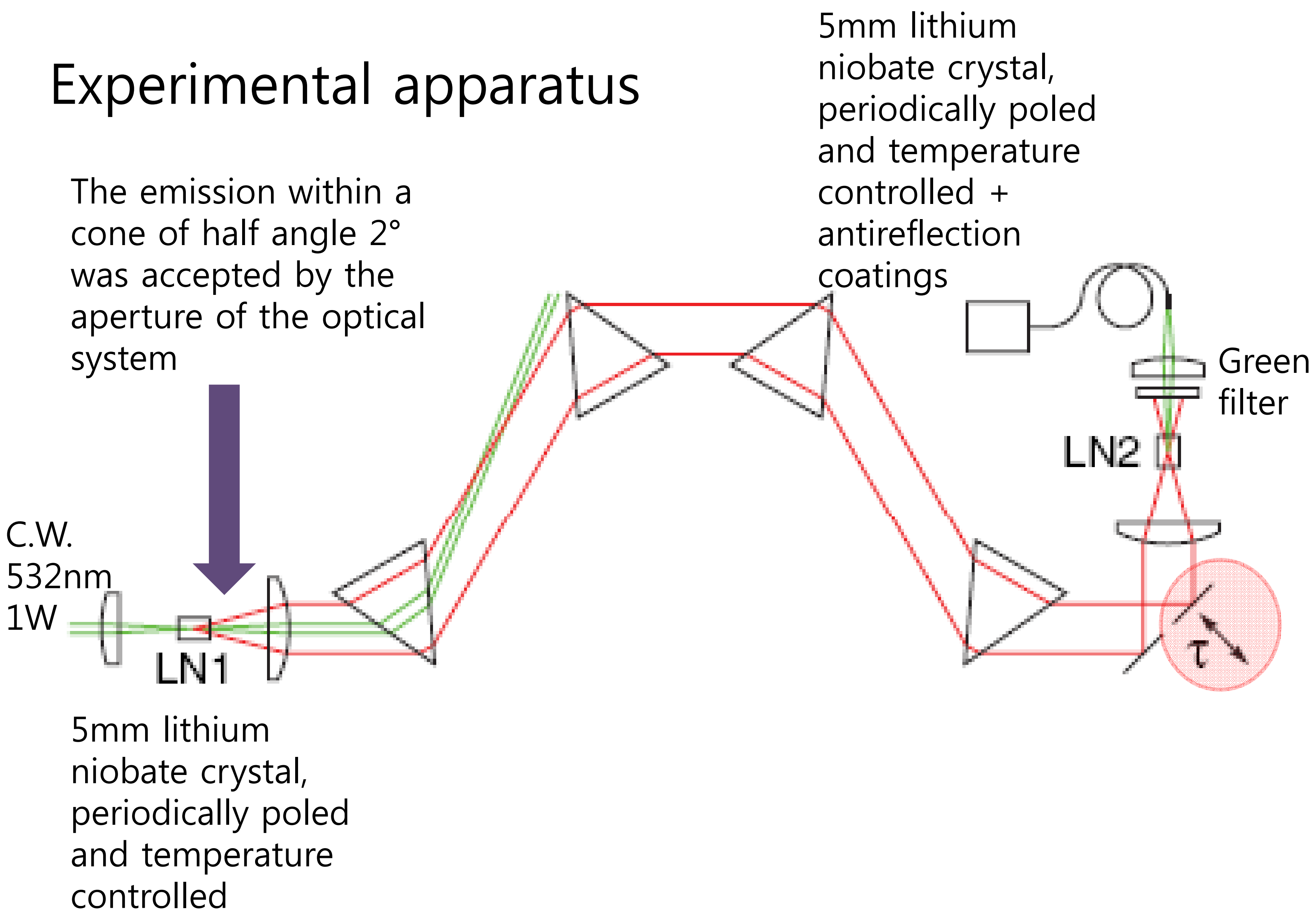
Theoretical considerations.

$$\left|\Psi_{UC}\right\rangle = \left|0\right\rangle + \kappa' \left|\Psi_{UC}^{(1)}\right\rangle$$

$$\left|\Psi_{UC}^{(1)}\right\rangle = \left[\int d\omega_s S(\omega_s) e^{i\omega_s \tau}\right] \hat{a}_u^\dagger(0, \omega_p)\left|0\right\rangle$$

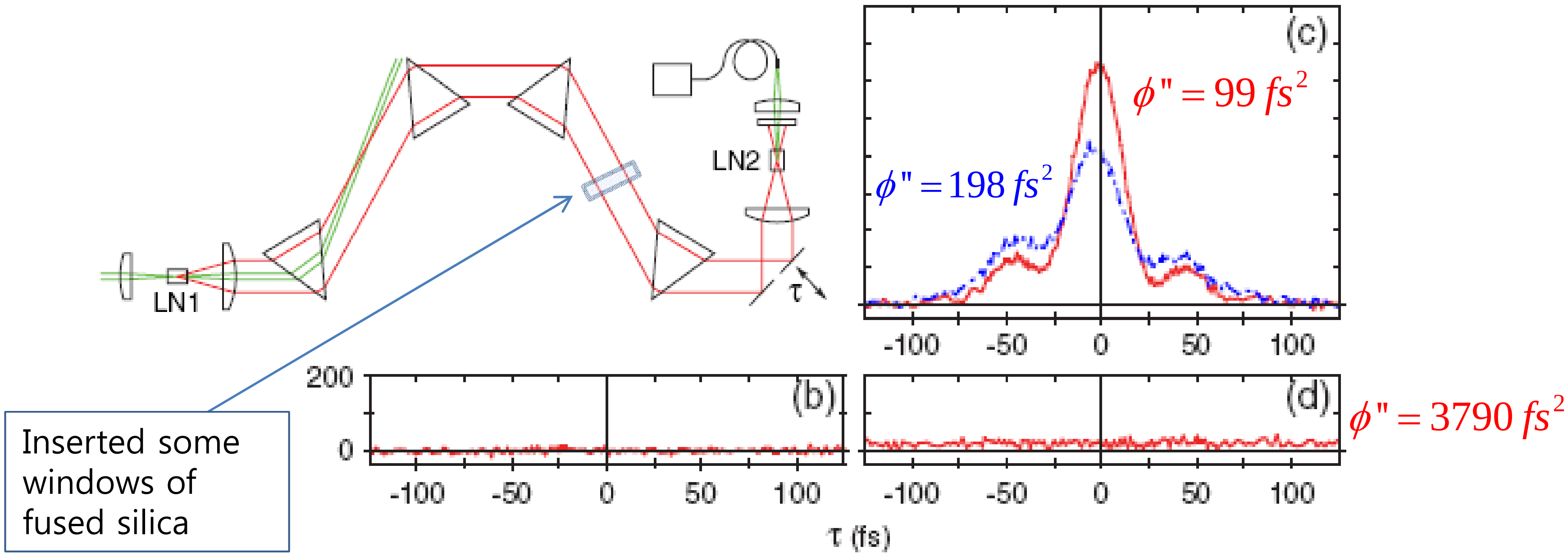
$$S(\omega_s) = \int d^2 \vec{k}_s^{\perp} \operatorname{sinc}^2(\beta) e^{-i\overline{\Delta}\overline{k}_z L} e^{i[\phi_s(\omega_s) + \phi_i(\overline{\omega}_i)]} p(\vec{k}_s) p(\overline{\vec{k}_i})$$

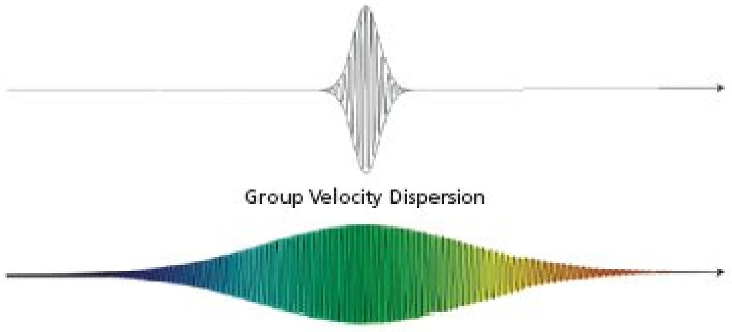
Experimental apparatus



Experimental Result

Count rate obtaind over 6 s, and subtracted dark count (195 s^{-1} , mesured over 30 s)





imental results. (a) Up-conversion delay τ for optimum dispersion. ystal 20 °C above phase-matching for additional signal-idler paths in curve], 12 mm of fused silica [(c), nm of SF10 glass (d), showing increasing broadening of $R(\tau)$. Data in (c),(d) have been scaled to correct for Fresnel window losses.

Theoretical Result

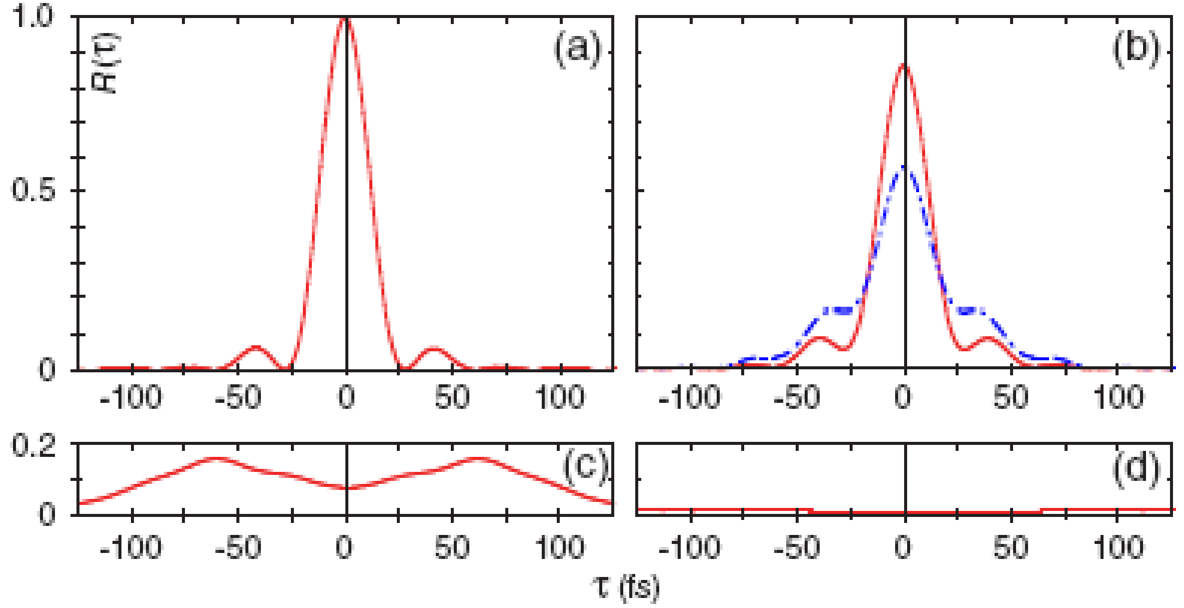


FIG. 3 (color online). Theoretical results. (a) Up-conversion rate $R(\tau)$ (arbitrary units) versus signal-idler delay τ for optimum dispersion. Also shown is $R(\tau)$ for additional common signal-idler dispersion due to 6 mm of fused silica [(b), solid curve, $\phi'' = 99\ \mathrm{fs}^2$], 12 mm of fused silica [(b), dot-dashed curve, $\phi'' = 198\ \mathrm{fs}^2$], 5 mm of SF10 glass [(c), $\phi'' = 513\ \mathrm{fs}^2$], and 37 mm of SF10 glass [(d), $\phi'' = 3790\ \mathrm{fs}^2$].